

1995107840

N95-14254

16103
P. 22

**F/A-18 AND F-16 FOREBODY VORTEX CONTROL,
STATIC AND ROTARY-BALANCE RESULTS**

**BRIAN KRAMER
BROOKE SMITH
EIDETICS AIRCRAFT, INC
TORRANCE, CALIFORNIA**

**NASA FOURTH HIGH-ANGLE-OF-ATTACK CONFERENCE
DRYDEN FLIGHT RESEARCH CENTER, EDWARDS, CA
JULY 12-14, 1994**

OUTLINE

The results of research on forebody vortex control on both the F/A-18 and the F-16 aircraft will be shown. Several methods of forebody vortex control, including mechanical and pneumatic schemes, will be discussed for the F/A-18 with examples of the force and moment data obtained. The wind tunnel data includes both static and rotary balance data for forebody vortex control. Time lags between activation or deactivation of the pneumatic control and when the aircraft experiences the resultant forces are also discussed. The static (non-rotating) forces and pressures are then compared to similar configurations tested in the NASA Langley and DTRC Wind Tunnel, the NASA Ames 80'x120' Wind Tunnel, and in flight on the High Angle-of-Attack Research Vehicle (HARV).

Similar experiments were conducted on the F-16 using both mechanical and pneumatic forebody vortex control methods. The F-16 wind tunnel results will be reviewed briefly followed by a discussion of simulation studies focused on evaluating the advantages of incorporating forebody vortex control capability into the flight control system of an F-16.

Finally, conclusions from these two programs will be highlighted.

PRESENTATION OUTLINE

- I INTRODUCTION**

- II F/A-18 WIND TUNNEL RESULTS**
 - EXPERIMENTAL SETUP
 - FOREBODY VORTEX CONTROL TECHNIQUES
 - TIME LAG
 - PRESSURE DATA
 - COMPARISON TO OTHER TEST DATA AND FLIGHT TEST

- III ENHANCED F-16 SIMULATION RESULTS**
 - YAW CONTROL POWER
 - 1v1 AIR COMBAT RESULTS

- IV CONCLUSIONS**

INTRODUCTION

The presentation covers the work conducted under two SBIR Phase II programs. The first, sponsored by NASA Ames (Technical Monitors Dr. Lewis Schiff and Dr. James Ross), was an investigation of forebody vortex control on a 6% F/A-18 model, with and without the influence of a rotary flow field. This research was part of the High Alpha Test Program (HATP), and was conducted in the NASA Ames 7'x10' Wind Tunnel.

The second SBIR Phase II program was sponsored by NASA Langley (Technical Monitor Mr. Daniel Banks). This program investigated forebody vortex control on the F-16, with three different forebodies. Static wind tunnel tests were conducted on a 10% F-16 model in the University of Toledo 3'x3' Wind Tunnel (forebody only) and in the NASA Langley 14'x22' Wind Tunnel. These results were then incorporated into a manned simulation.

INTRODUCTION

F/A-18

- **STATIC AND ROTARY BALANCE TESTS WERE PERFORMED ON A 6% F/A-18 DURING AN SBIR PHASE II PROGRAM SPONSORED BY NASA AMES (HATP).**
- **PRIMARY OBJECTIVE: DETERMINE EFFECTIVENESS OF SEVERAL TYPES OF FVC IN A ROTARY FLOW FIELD**

F-16

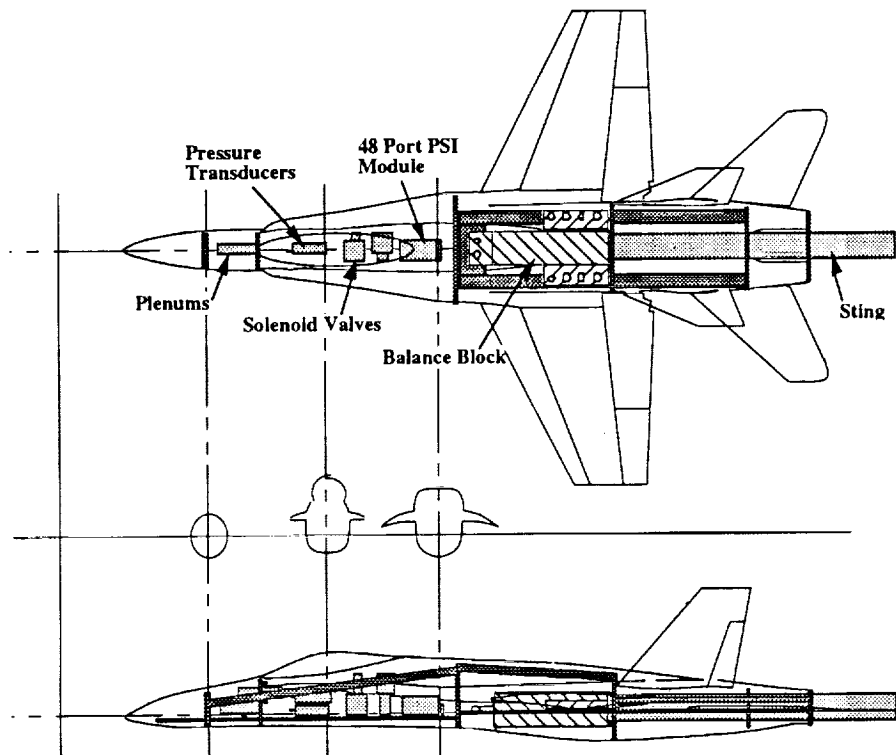
- **NASA LANGLEY SBIR PHASE II LOW-SPEED WIND TUNNEL TESTS WITH A 10% F-16 MODEL**
- **PRIMARY OBJECTIVE: SYSTEMATIC EVALUATION OF MECHANICAL AND PNEUMATIC FOREBODY VORTEX CONTROL.**
- **SECONDARY OBJECTIVE: EVALUATION OF FVC UTILITY WITH F-16**

F/A-18 WIND TUNNEL MODEL

The model for these experiments is a new 6%-scale F/A-18 model designed and built by Eidetics International. The model exterior lines were determined by borrowing the Navy/McAir 6%-scale force and moment steel model to make a pattern and permanent mold. From this mold, a fiberglass shell with an accurate external shape was fabricated. The forebody part of the mold was then also used to make several forebody (nose portion only) model pieces.

The model structural design was required to accommodate the loads of both the static test and the rotary-balance tests. The fiberglass shell of the model attaches to a structure that consists of base plates, six aluminum bulkheads and stringers. The structural center of the model is a stainless steel balance block with mounting tabs for the wing and the base plates. The wings have a steel core to carry the aerodynamic loads, and the airfoil shape is built up with wood and fiberglass around the structural center. The leading and trailing-edge flaps and ailerons were all deflectable; however, the test was conducted with the leading edge flaps only in the maneuver position (34°) and the trailing-edge flaps undeflected. The ailerons were tested in the plus and minus 10° positions to estimate roll control power. The vertical tails have an aluminum core and rudders that can be deflected plus and minus 30° . The horizontal tails were fixed at 0° for the entire test.

6% F/A-18 WIND TUNNEL MODEL



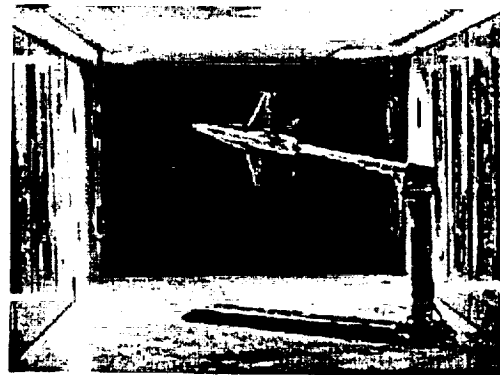
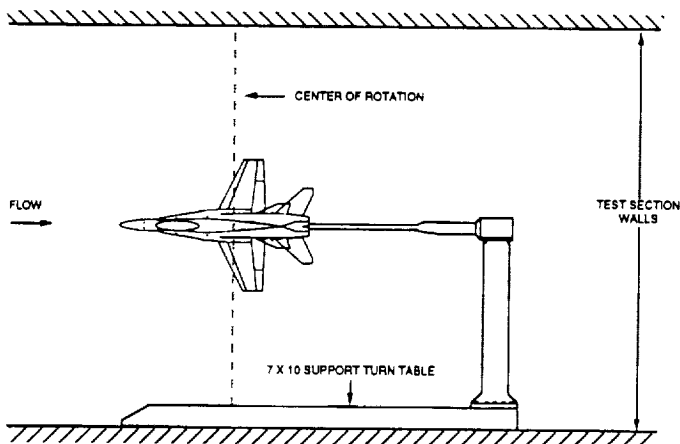
STATIC WIND TUNNEL TEST INSTALLATION

The model was sting mounted on a dog-leg and turntable system. The model was mounted on the sting at a 90° roll angle (wings vertical) and the model was pitched in the horizontal direction with the floor mounted turntable. Sideslip angles were introduced by inserting angled wedges between the sting base and the vertical strut. The tests were run at a dynamic pressure of 27 psf (approximately 150 ft/sec) and a Reynolds number of 0.92×10^6 per foot. A few runs were made at dynamic pressures of 10 psf ($V=90$ ft/sec and $Re=0.56 \times 10^6$ per foot) and 20 psf ($V=131$ ft/sec and $Re=0.8 \times 10^6$ per foot) to explore Reynolds number differences. The angle of attack was varied from 0° to 60°, and the sideslip angle at 0° or -10°.

FOURTH NASA HIGH ALPHA CONFERENCE

E I D E T I C S

STATIC WIND TUNNEL TEST INSTALLATION



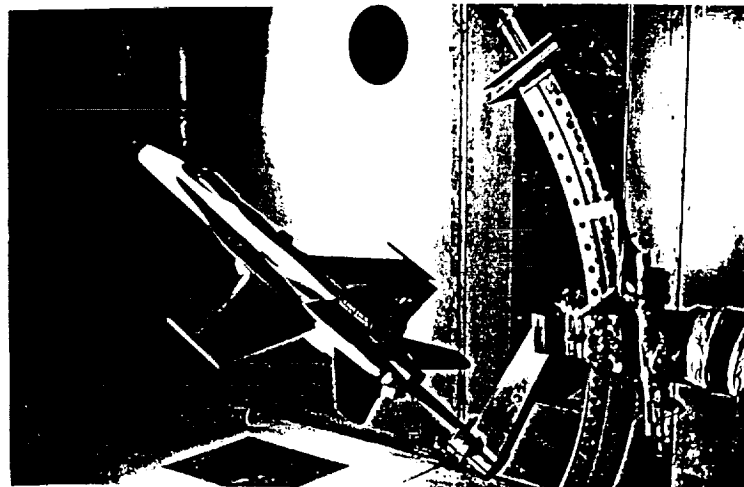
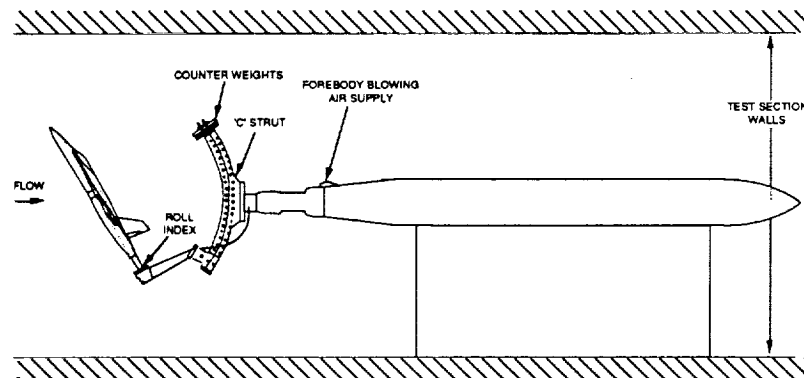
ROTARY BALANCE WIND TUNNEL TEST INSTALLATION

Rotary-balance experiments determine the forces and moments of a model in a steady rotational motion about the velocity vector at fixed angles of attack and sideslip. Rotation around the velocity vector is considered to be a key maneuver for enhanced agility in combat for modern fighter aircraft. In order to properly assess the control power to produce a robust velocity vector roll (known as a loaded roll because the aircraft is rolling with significant lift forces due to angle of attack), it is necessary to not only determine the yaw and roll moments statically, but dynamically at the appropriate roll rates.

The focus of the present rotary-balance wind tunnel experiments was to evaluate in a rotary motion the best forebody vortex control techniques determined from the previous static tests. The maximum rotation rate required in the wind tunnel is determined by matching the non-dimensional roll rate, expressed as $\omega b/2V$, where ω is the rotation rate (rad/sec), b is the wing span and V is the free stream velocity. If we choose a typical condition for a full-scale F/A-18 as velocity-vector roll rate of $60^\circ/\text{sec}$ (up to 60° AOA) and free stream velocity of 150 ft/sec, then the non-dimensional rotation rate around the velocity vector would be 0.1396. For higher velocities, the non-dimensional parameter would be even less. The maximum rate of the rig during the experiments was 200 rpm, which resulted in maximum non-dimensional rotation rates of 0.175 for $V=150$ ft/sec.

The rotary rig was based on the hydraulics of the system last used in the Ames 6 x 6-Ft Wind Tunnel in 1984. New hardware was designed to provide manual changes in angle of attack and sideslip by moving and pinning the sting assembly to pre-drilled hole locations (every 3° from 0° to 60°) on the C-strut. Angles of sideslip at specific angles of attack are provided by rolling the straight sting around its own axis in the strut arm in combination with the appropriate angle setting on the C-strut.

ROTARY BALANCE WIND TUNNEL TEST INSTALLATION



FOREBODY VORTEX CONTROL CONFIGURATIONS

The nose section of the model was removable so that different forebody vortex control devices could be studied by replacing the nose section. There were five blowing jet positions, three of which were at 135° azimuth from the windward meridian, at three fuselage stations (Noses 1, 2, 3). The middle position ($x = 0.93$ inches model scale) corresponded to the furthest aft fuselage station that was tested in the 1992 test of the F/A-18 in the 80x120 Foot Wind Tunnel at NASA Ames. The furthest aft position ($x = 1.30$ inches) corresponds to 0.5 equivalent nose diameters aft of the nose tip. At this fuselage station, in addition to the jet at 135°, there were jets at 150° and 120° (Noses 4 and 5). Only the results from the most effective jet configuration (Nose 4 with the jets angled inboard 60°) will be shown.

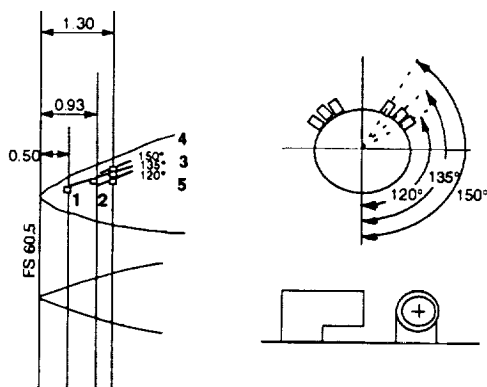
In addition to the jet blowing noses, there was a slot blowing nose. The slot width was held to a reasonably constant width (0.006 inches) with small metal shims between each of the four segments (A,B,C and D). Unlike the full scale aircraft, size constraints made it impossible to have separate supply pressure lines to each slot segment. Instead, the interior of the nose was made into two plenums, one for the left side and one for the right, that supplied all of the segments. The slot size tested was 0.006 inches wide with a length of 2.58 inches beginning 0.56 inches from the nose tip. This was the slot configuration that showed the highest effectiveness in a 1992 test of the F/A-18 in the 80x120 Foot Wind Tunnel at NASA Ames. Different slot lengths were tested by taping over portions of the slot. The most effective slot configuration was with segments A and B blowing.

In addition to the pneumatic control systems, several mechanical, miniaturized strake configurations were tested. Only the results from the single rotating nose tip strake, and a vertical, pivoting, nose strake (the Rhino Horn) will be shown here. Although similar in shape to the rotating nose tip strake, the Rhino Horn is mounted on the leeward meridian line of the forebody and pivots about an axis perpendicular to the surface of forebody.

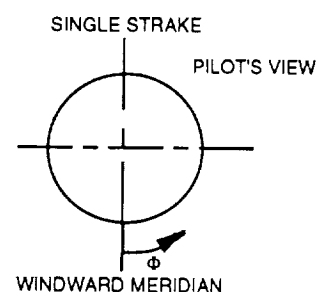
FOURTH NASA HIGH ALPHA CONFERENCE

E I D E T I C S

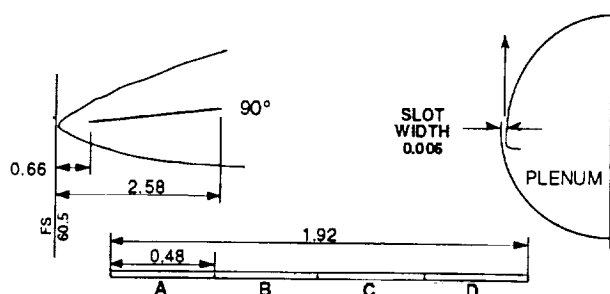
FOREBODY VORTEX CONTROL CONFIGURATIONS



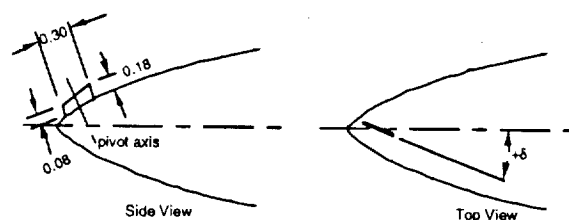
JET BLOWING



SINGLE STRAKE



SLOT BLOWING

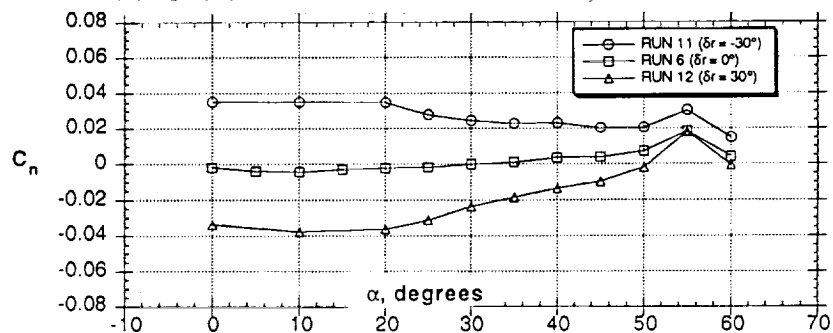


RHINO HORN

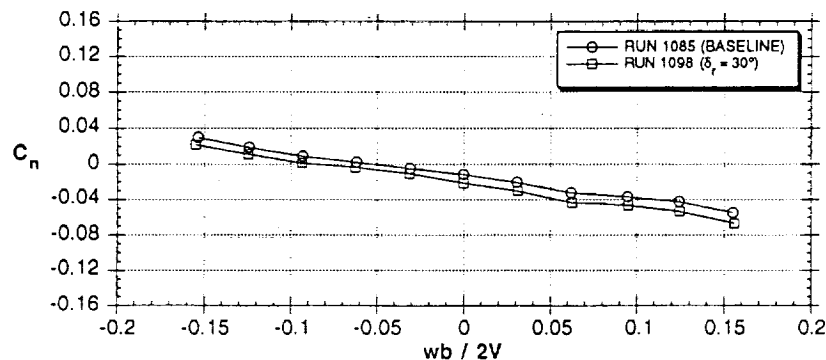
BASELINE RUDDER EFFECTIVENESS

The static wind tunnel test results show the primary reason for the interest in forebody vortex control. As the angle of attack is increased above 20°, the rudder effectiveness drops rapidly to near zero at 50°. The rotary balance results show that the static level of rudder effectiveness remains the same, and in fact, the increment from the baseline stays basically constant. The slope of the line with different dimensionless rotation rates indicates that the baseline F/A-18 has an anti-spin characteristic that is not effectively changed by the rudder deflection (the lines are parallel).

BASELINE RUDDER EFFECTIVENESS



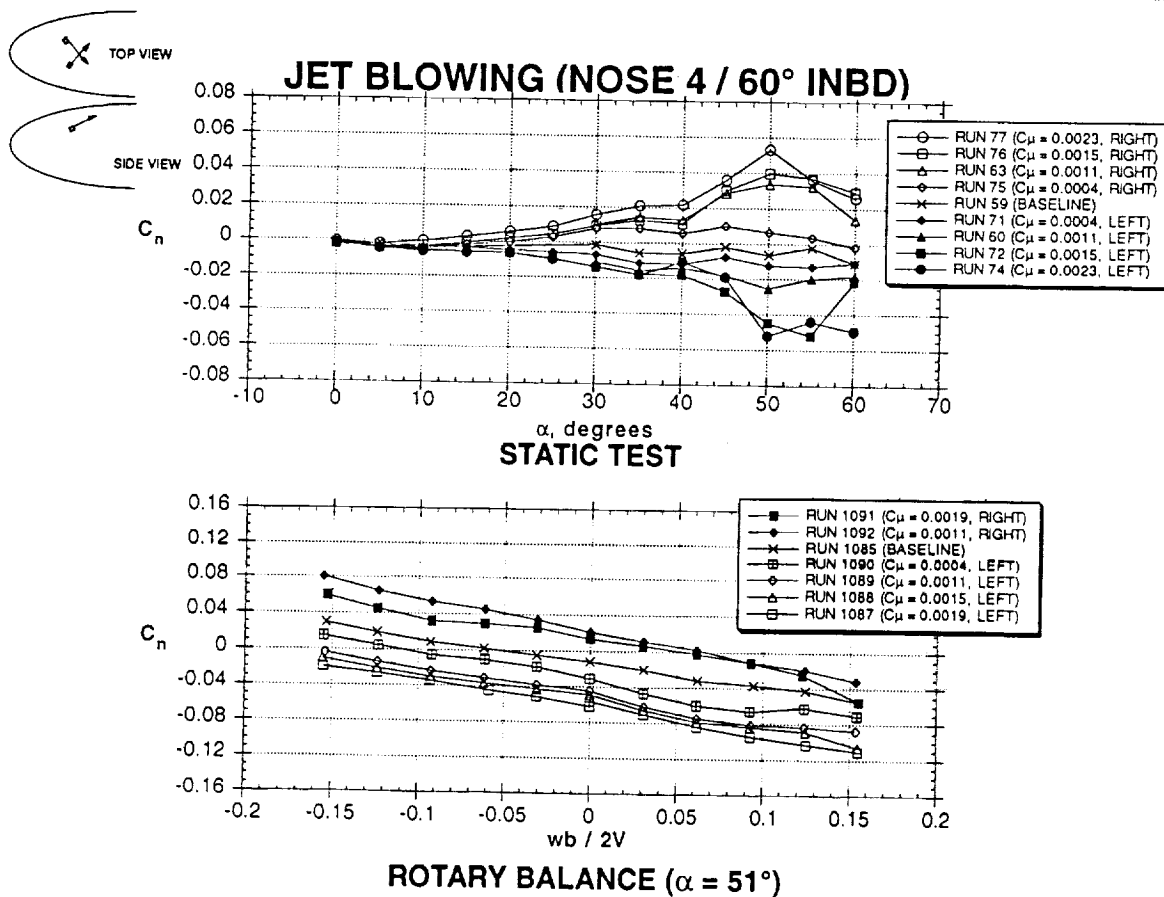
STATIC TEST



ROTARY BALANCE ($\alpha = 51^\circ$)

JET BLOWING

Jet blowing proved to be effective beginning at 20° to 30° AOA in the static test. As the angle of attack was increased, the effectiveness increased as the forebody vortex strength increased. Increasing the blowing rate tended to increase the yawing moment in a well behaved manner and, as previously observed, blowing on the right hand side of the body produced a positive yawing moment (and vice-versa). The rotary balance data showed very similar behavior, with very little degradation due to the rotating flow field. The blowing cases are similar to the rudder in that they only cause an offset to the baseline without effecting the slope (anti-spin tendency).



TIME LAG

An investigation was made to determine whether there is a significant time delay from activation of jet blowing to the time when the aircraft experiences a "fully transitioned" change in the yawing moment. The time lag is important not only for the onset of blowing control, but also for the decay time after the jet is turned off. The time lag was measured by looking at the pressure field response on the surface of the model with Endevco dynamic pressure sensors. In addition, the balance outputs were recorded in raw counts, but not reduced to forces or coefficients. As a reference point, the time that it takes the flow to traverse the length of the model fuselage (convective time) is 22 msec.

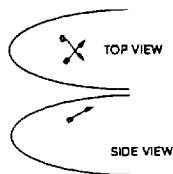
When the solenoid valve opens (at 0.065 sec), there is a finite period of time required for the plenum pressure to establish (~45 msec). At about 0.090 sec, Endevco #1 begins to respond. Because of the proximity of Endevco #1 on the forebody to the blowing jet, it is apparent that there is a pneumatic lag from not only the plenum filling but also the tubing length from the plenum to the jet exit. By 0.140 sec, Endevco #1 indicates that the flow is fully established at this point on the body. The other Endevcos shown, as well as those not shown, do not sense any change in the flow field caused by the blowing. This is in agreement with the static pressure data discussed above which also saw most of the effect only on the forebody. Perhaps more conclusive evidence of the time lag period is seen by examining the balance output. Here it is clear that by 0.130 sec the new steady state yawing moment has been established. Therefore, a conservative estimate of the time lag for the onset of control (including large pneumatic lags) would be 65 msec (just over 3 convective times). If the pneumatic lags were removed, the time lag would be on the order of 40 msec or about 2 convective time units.

The behavior is very similar for the decay of the yawing moment when the blowing valve is closed (at 0.500 sec.). In about 80 msec, the yawing moment has returned to the pre-blowing level. If the pneumatic lags were once again removed, the time lag would be on the order of 60 msec or about 3 convective time units.

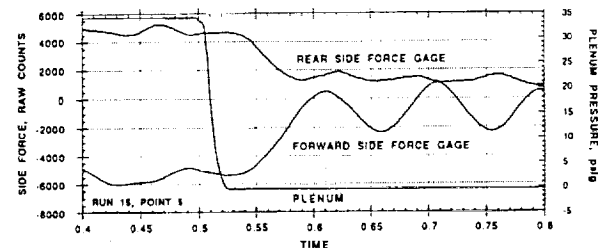
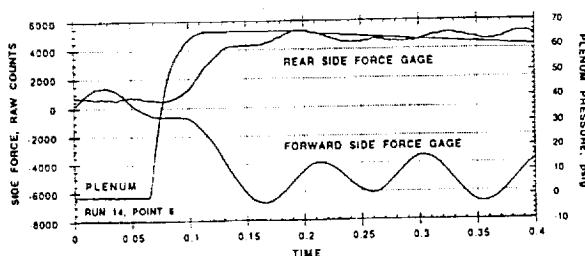
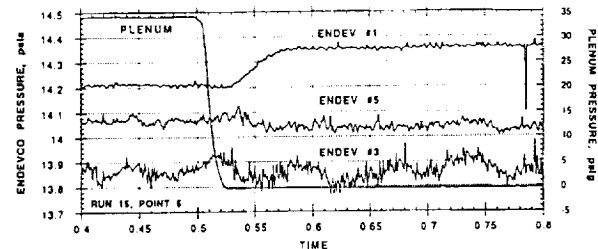
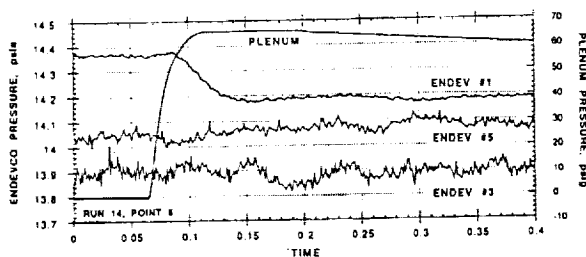
As a point of reference, the full scale F/A-18 requires approximately 2 convective time units to fully deflect its rudder (moving at 60°/sec).

FOURTH NASA HIGH ALPHA CONFERENCE

E I D E T I C S



TIME LAG OF FVC COMMAND ($\alpha = 51^\circ$)

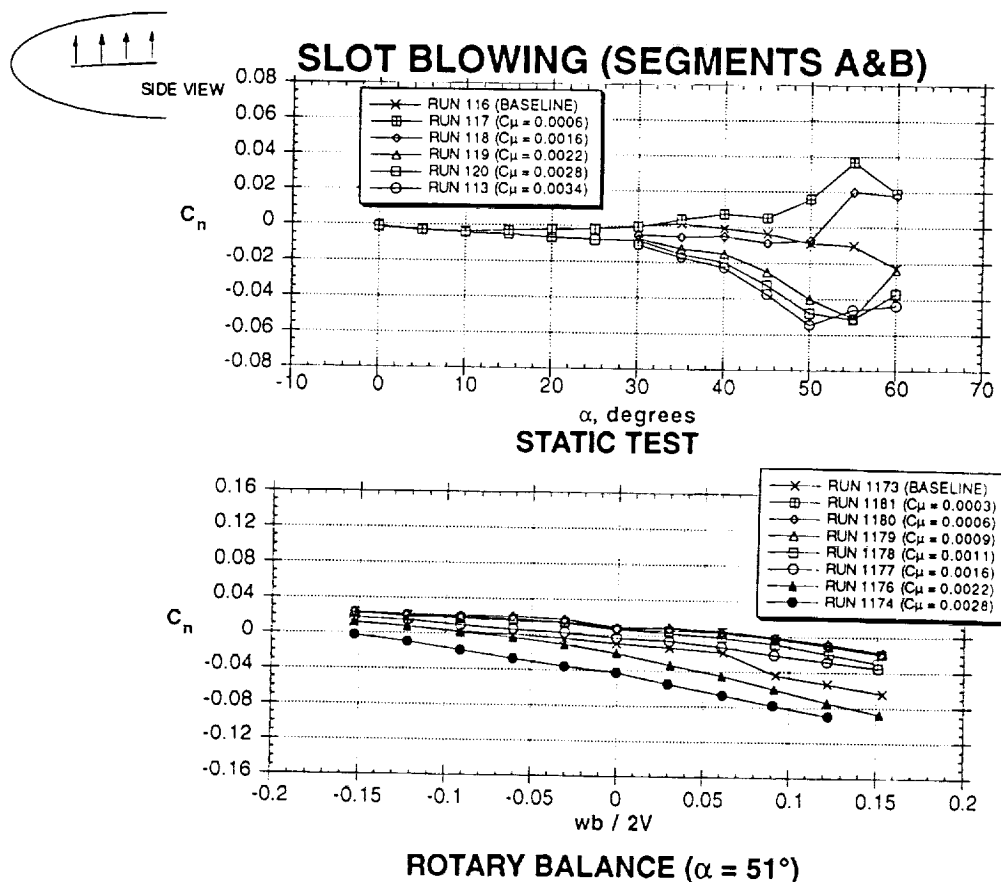


ONSET

DECAY

SLOT BLOWING

The blowing slot is shown for left side blowing only. When low blowing rates are applied, the yawing moment is positive, or to the right side. As the blowing rate is increased, the yawing moment shifts over to the negative, or left side. This behavior is probably due, at least in part to the difficulty in building the slot at this scale. Flow visualization revealed that there was a fairly large forward component in the slot velocity, as well as the desired tangential flow. The rotary balance results yield the same results at zero rotation, but the effect of rotation direction is seen to have a relatively large effect. As the model is rotated in the negative direction, the left hand blowing slot is on the windward side of the fuselage, and the level of maximum of incremental yawing moment reduces. Likewise, as the model is rotated in the positive direction, the slot becomes more effective. It should be noted that blowing on the right side had the opposite effect.

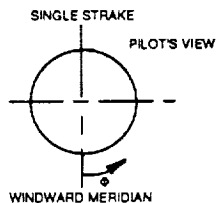


SINGLE ROTATING NOSE TIP STRAKE

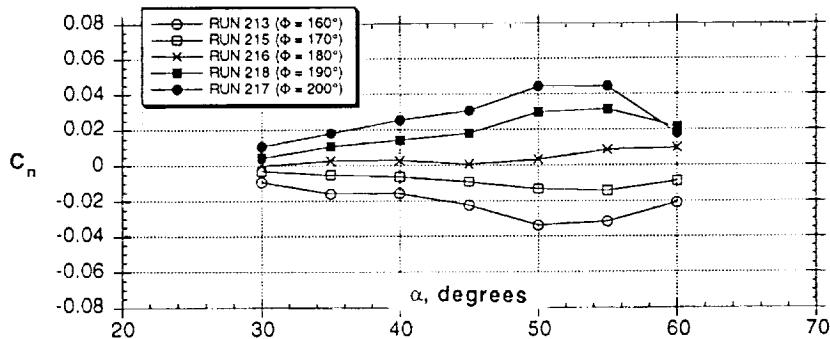
The single rotating nose tip strake had very well behaved incremental yawing moment trends with angle of attack about the leeward side of the nose (top). In a rotary flow field, the strake has an increased level of anti-spin damping, when the strake is in the 180° position. However, when the strake was deflected, it could arrest or initiate a rotary motion throughout the range of rotations that were tested.

FOURTH NASA HIGH ALPHA CONFERENCE

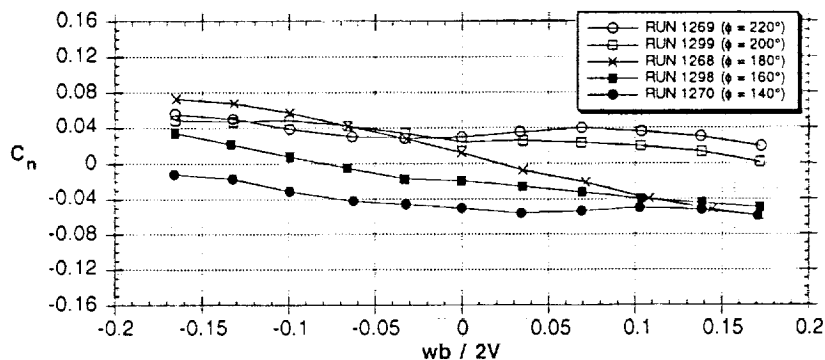
E I D E T I C S



SINGLE ROTATING NOSE TIP STRAKE



STATIC TEST



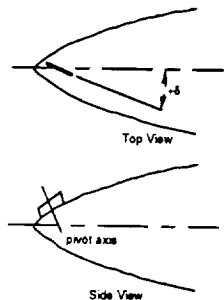
ROTARY BALANCE ($\alpha = 51^\circ$)

RHINO HORN

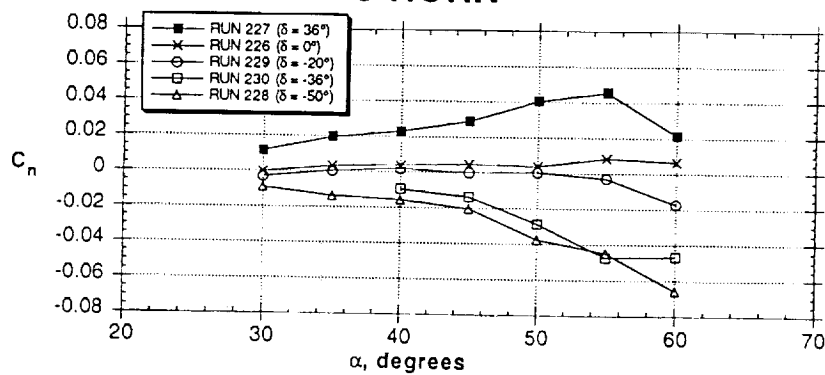
The Rhino Horn behaved similarly to single rotating nose tip strake and was well behaved up to 60° AOA. The rotary test showed that the presence of the strake increased the anti-spin tendency (greater negative slope) as well. At the maximum negative rotation rate, the Rhino Horn is unable to generate any additional positive yawing moment. However, the yawing moment generated in the undeflected case is greater than 0.08, which is considerably greater than the baseline aircraft's 0.04. This indicates that an active control system could be used to obtain a large envelope of control power, which will be discussed later. The Rhino Horn produced a larger range of achievable yawing moments across the range of reduced rotation rates than any other device tested.

FOURTH NASA HIGH ALPHA CONFERENCE

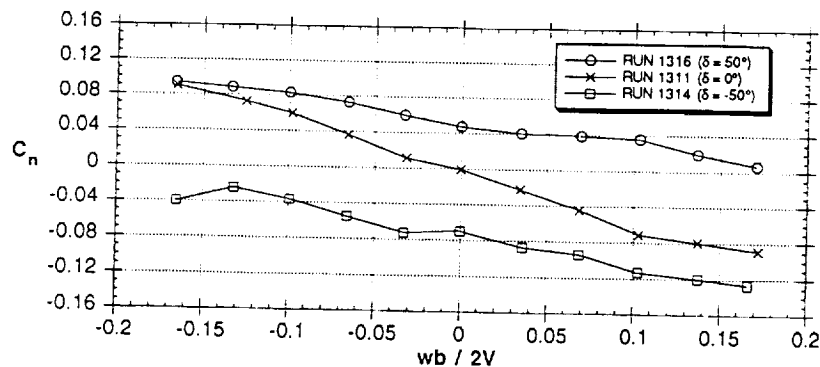
E I D E T I C S



RHINO HORN



STATIC TEST



ROTARY BALANCE ($\alpha = 51^\circ$)

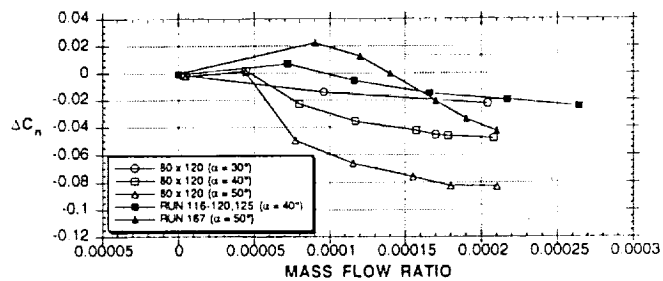
YAWING MOMENT COMPARISON

The comparison of the slot blowing data to that obtained in the 80'x120' wind tunnel shows some significant differences. The most probable culprit is the quality of the flow out of the 6% model slot. A better system of baffling the air in the plenum could help prevent some of the poor exit conditions from the slot. The jet blowing data compares somewhat better. The mass flow ratio achieved in the 6% test was even less than that obtained in the full scale test, but neither one is very effective at producing yawing moment at any angle of attack. The comparison of the rudder power generated by a 30° deflection is good.

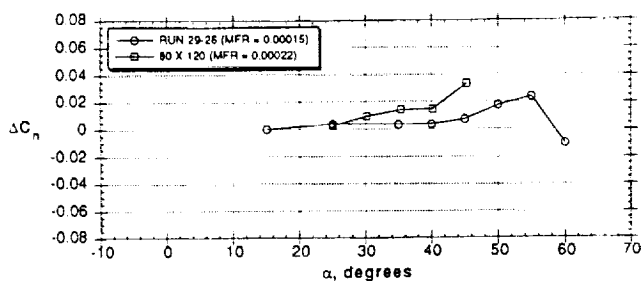
FOURTH NASA HIGH ALPHA CONFERENCE

E I D E T I C S

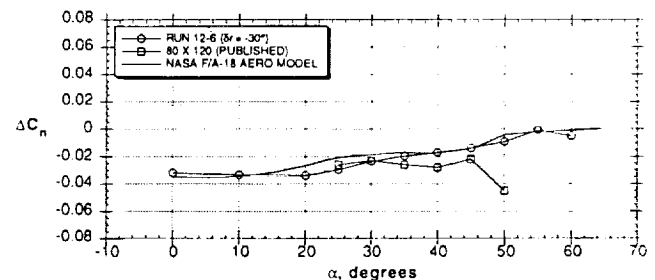
YAWING MOMENT COMPARISON WITH NASA AMES 80'X120'



SLOT BLOWING SLOT AB



JET BLOWING
STRAIGHT AFT, NOSE

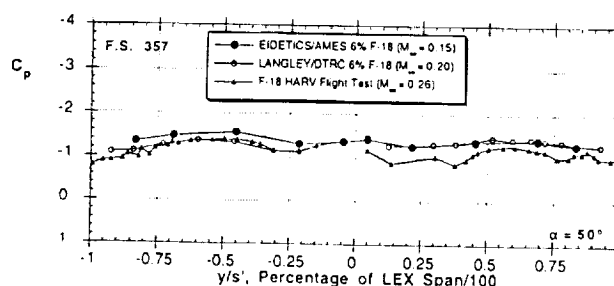
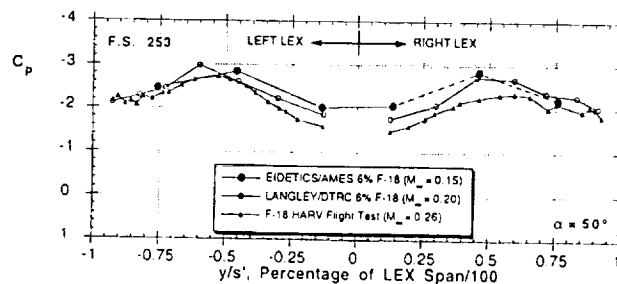
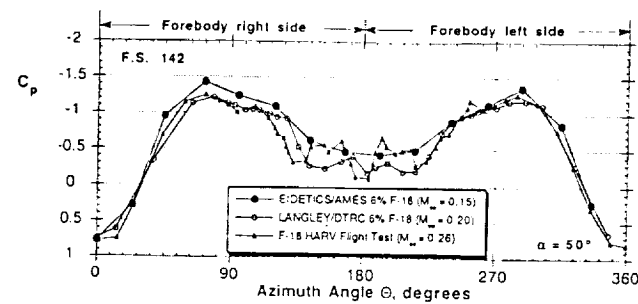


30° RUDDER

FOREBODY PRESSURE COMPARISON

The pressure distribution on the forebody is compared with the HARV F/A-18 and another 6% model tested by NASA Langley at the Navy's DTRC facility. The density of pressure ports was much greater for both of these than for the present test. The agreement overall is very good, however the HARV shows very clearly the location of the primary and secondary vortices. The sub-scale models fail to capture these peaks, although some of this could be due to a lack of density of the pressure ports. The current test also shows a slightly greater negative pressure than the other two tests.

FOREBODY PRESSURE COMPARISON TO HARV AND NASA LANGLEY

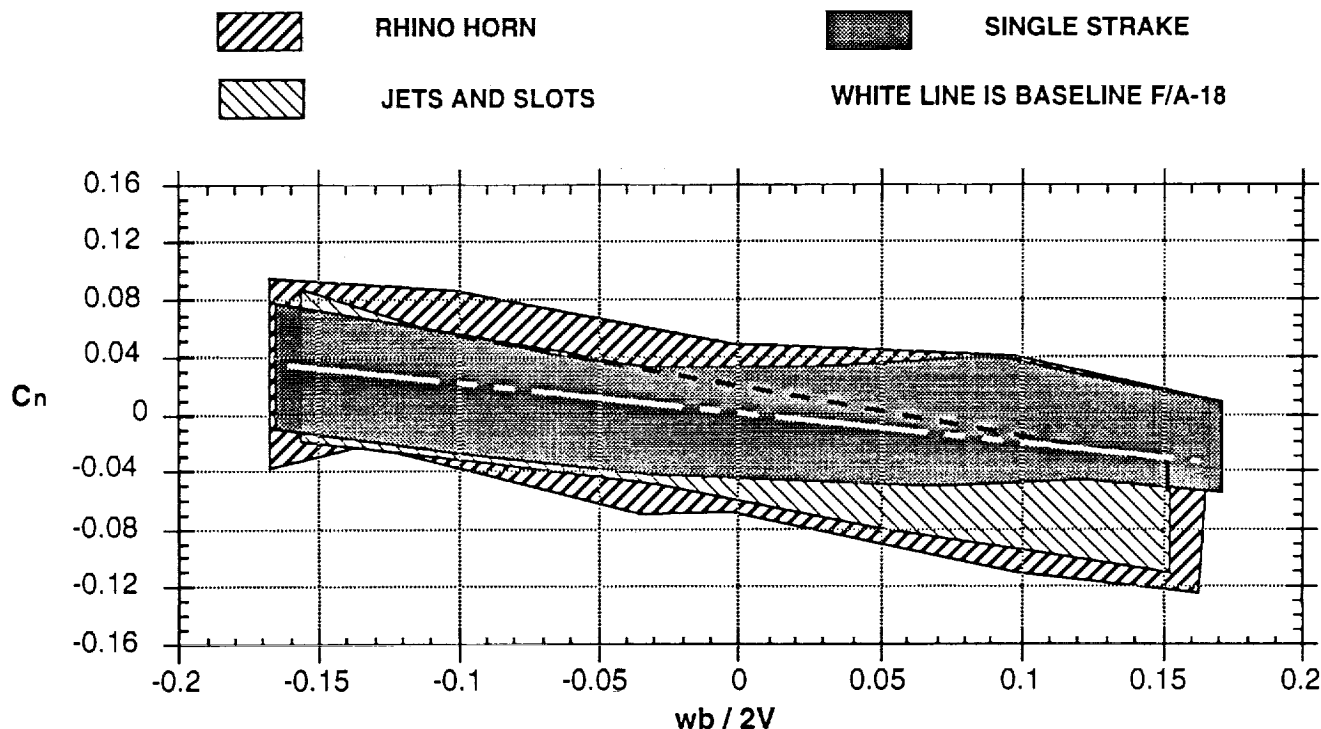


YAW CONTROL POWER ENVELOPE

The yaw control envelopes for all of the devices tested were created by simply shading in the area that corresponded to the largest positive and negative yawing moments achieved by each device. The baseline F/A-18 is shown as the white line. The Rhino Horn had the largest envelope of effectiveness, with the ability to create large (>0.04) yawing moment increments in either direction at any rotation speed. These envelopes show the possibilities for control that are available for either a stability augmentation system (SAS) or command augmentation system (CAS).

YAW CONTROL POWER ENVELOPE OF FVC DEVICES

$$\alpha = 51^\circ$$



F-16 CONFIGURATION AND CONTROL TEST MATRIX

The methods of forebody vortex control (FVC) investigated during the F-16 wind tunnel tests were similar to those tested with the F/A-18. The tests parametrically varied a range of FVC characteristics, including blowing jets and slots and rotating miniature noseboom strakes, in an attempt to systematically sort out the design sensitivities and establish some guidelines for application.

The overall control characteristics of the F-16 FVC devices were similar to the F/A-18, in spite of a few geometry differences. For example, the mechanical rotating strakes were mounted on the F-16 nose boom instead of on the tip of the nose as with the F/A-18. And of course, the F/A-18 forebody cross-section is roughly elliptical with a vertical major axis whereas the F-16 forebody is horizontally oriented. The Shark and Chine nose geometries are even more flattened horizontally. Generally, the FVC behavior already presented for the F/A-18 configuration also is applicable to the F-16 (and derivatives) and will not be reviewed again. Instead, the focus of the following discussion will be the evaluation of FVC on the F-16 using manned simulation.

F-16 CONFIGURATION AND CONTROL MATRIX

		DIFFERENT FOREBODY GEOMETRIES		
		BASELINE F-16	USAF CHINE	EIDETICS SHARK NOSE
FOREBODY VORTEX CONTROL SCHEMES	ROTATABLE NOSE BOOM STRAKES	EFFECT OF ROTATION ANGLE ($\pm 180^\circ$) ON-AXIS AND OFFSET CONFIGURATIONS DIFFERENT PLANFORM SHAPES AND AREAS EFFECTS OF LONGITUDINAL POSITION ON BOOM		
	BLOWING JETS	DIFFERENT BLOWING RATES 4 LONGITUDINAL LOCATIONS ALONG NOSE 2 RADIAL POSITIONS MULTIPLE BLOWING ANGLES		
	BLOWING SLOTS	DIFFERENT BLOWING RATES 2 RADIAL POSITIONS VARYING SLOT LENGTH		

SIMULATION CONFIGURATIONS

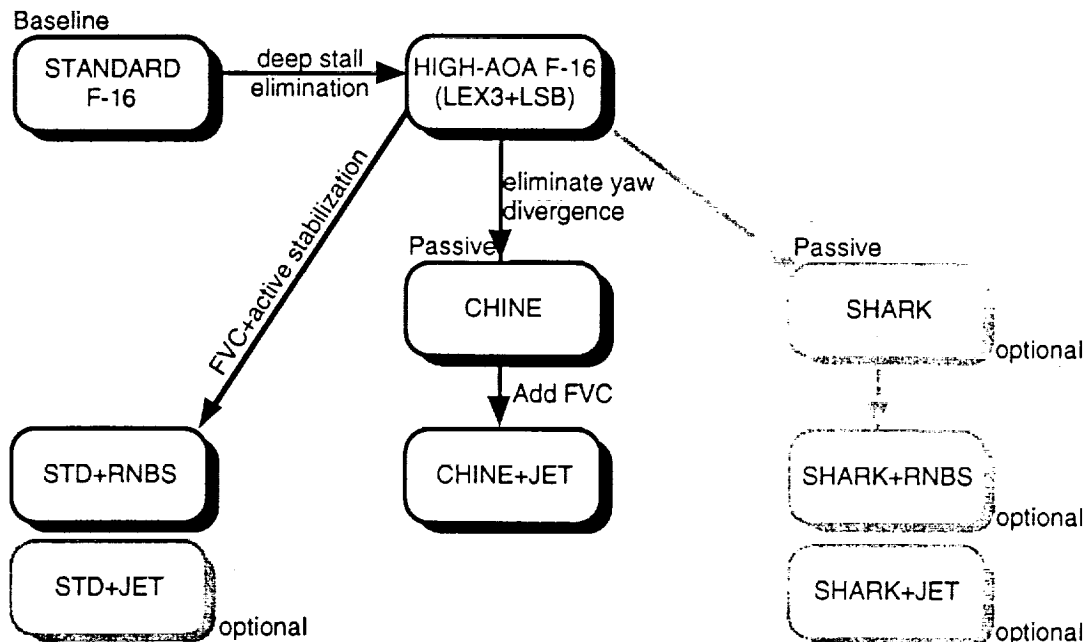
After completing the static wind tunnel study, the F-16 project turned to a simulator study of the in-flight utility of FVC. The "best" FVC techniques from the wind tunnel tests were selected, new flight control systems designed, agility metrics quantified, and then 1v1 air combat trials were conducted.

Before the F-16 can be an effective high-angle-of-attack aircraft some other modifications must be made. Shortening the wing leading-edge extension (LEX) and adding a larger speedbrake (LSB) eliminates the deepstall, provides greater nose-down pitch agility and improves the lateral/directional characteristics (through coupling of the forebody, LEX and wing vortices). The baseline F-16 has a static directional instability at angles of attack above 32° and also develops large yaw moments at zero sideslip due to asymmetric forebody vortex formation at higher angles of attack. The Chine and Shark nose variants stabilize the forebody vortices and passively eliminate the yaw instability.

The five configurations shown in the figure were investigated in the simulation task.

- STANDARD F-16: Benchmark for enhancements
- HI-AOA F-16: Deepstall eliminated, AOA limit removed. Still directionally unstable.
- PASSIVE CHINE: Directionally stable, a true conventionally controlled high AOA airframe.
- CHINE + JET: Pneumatic FVC added for hi-AOA maneuverability.
- STD + RNBS: Standard forebody with cut-back LEX and LSB. Uses rotating nose boom strake for control and active yaw stabilization.

F-16 CONFIGURATIONS FOR SIMULATION



YAW CONTROL POWER

STANDARD F-16

The yaw moment due to \pm maximum deflections of the rudder are shown in the central figure. The rudder control power is constant up to 30° angle of attack where it begins to decrease. The rudder is virtually ineffective above 50° angle of attack. Note that the yaw moment magnitude is 0.045. This model developed a yaw moment asymmetry at high angles of attack.

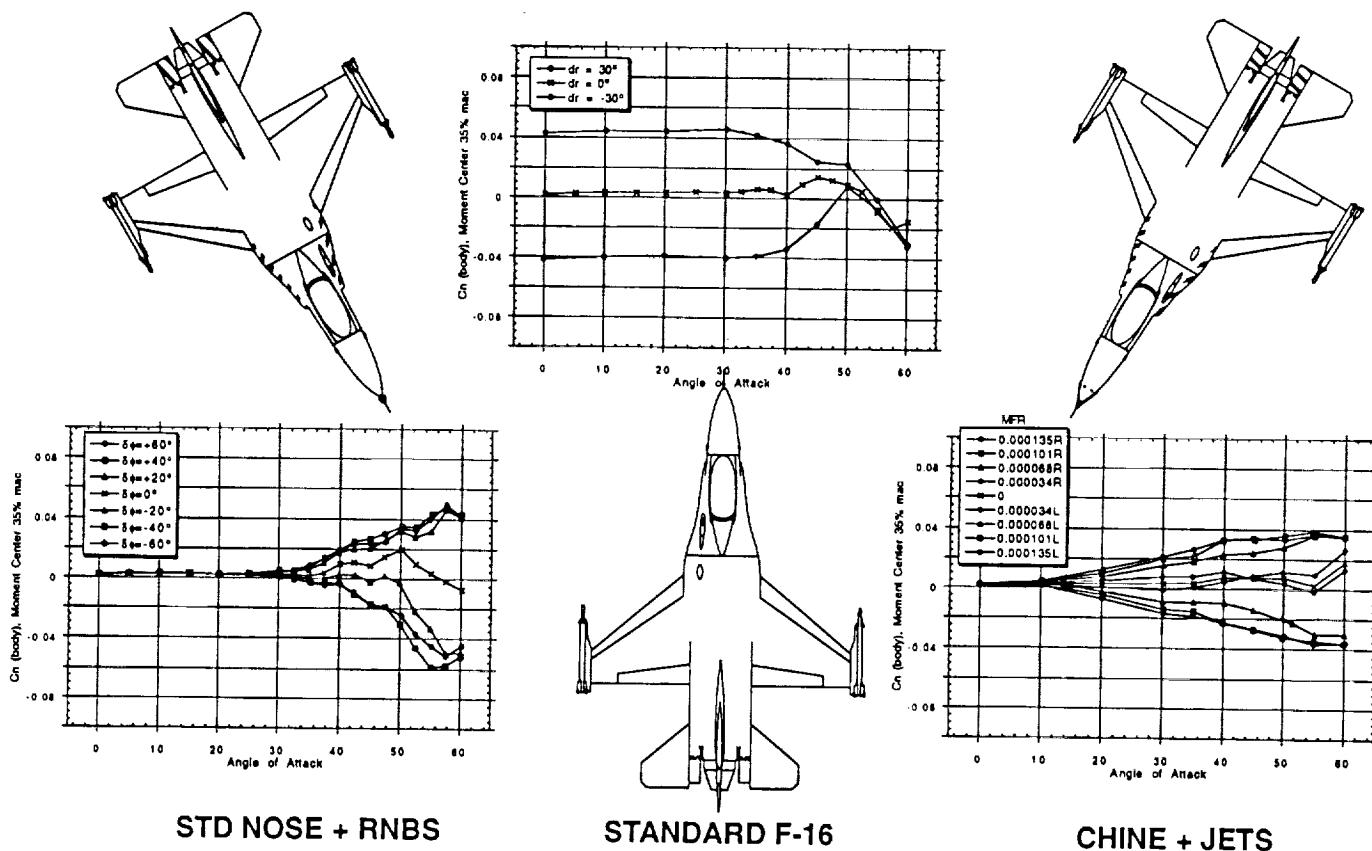
STD NOSE + RNBS

The yaw control power developed by the rotating nose boom strake (RNBS) is shown on the left hand plot for various strake rotation angles. Like the F/A-18 the strake does not become effective until the angle of attack is greater than 30° . Note that this configuration includes the cut-back LEX and large speed brake as shown in the sketch.

CHINE + JET

Mechanical FVC was not effective when used in combination with the Chine. The effectiveness of jets angled across the forebody is shown in the right figure. The jets produce yaw control moments over a larger angle of attack range than the RNBS. Note that the magnitudes of the yaw control power at high angles of attack are roughly equal to that produced by the rudder at low AOA.

F-16 YAW CONTROL POWER



TYPICAL TRACKING MANEUVER

These plots illustrate a typical change of maneuver plane during a tracking task as performed by the standard F-16 and an FVC enhanced configuration. The plot shows the angular orientation of the aircraft's body axis (θ and ψ) at discrete moments during the maneuver. The long line extending from the aircraft symbol represents the angle of attack and the shorter leg is sideslip. The end of the "L" opposite the aircraft symbol shows the velocity vector (γ and σ). The numbers show the flight time in seconds. This technique of presenting flight data was developed by Yuri Kalviste (AIAA-86-2283).

The most striking difference between the two examples is that the FVC aircraft is much smoother in its maneuvering to acquire and track the target. The use of higher angles of attack and sideslip are apparent, as is the use of velocity vector maneuverability at high angles of attack. The standard F-16 maneuver plot reflects the pilot's explanation of the maneuver technique as, "pull - unload - roll - pull - unload - roll, repeat."

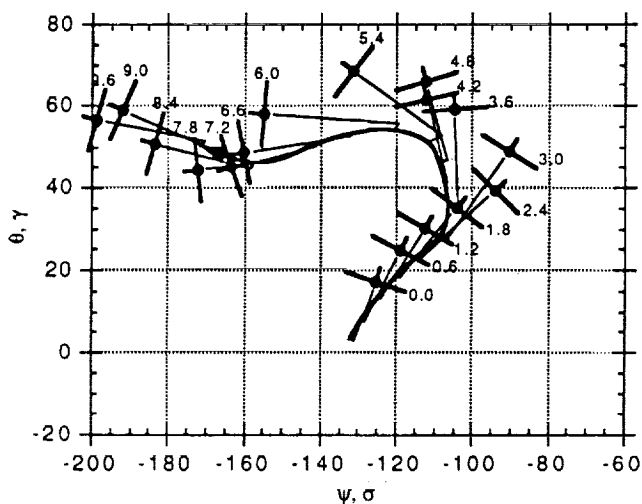
Other pilot comments from the post-flight de-briefs and questionnaires were that the FVC aircraft required a different piloting technique that was much smoother than used with the baseline aircraft. The smoother technique made it easier to set-up for a shot, allowed adjustments of the maneuver plane, and would provide additional shot opportunities during air combat. Other differences between the configurations that were seen during the air combat trails were the use of the increased nose-down pitch agility and rapid deceleration in a defensive position to force an overshoot. Rapid deceleration is possible due to the high drag associated with post-stall angles of attack.

By and large, these were the expected benefits to be obtained with capability to maneuver at high angles of attack. These advantages became apparent during a prolonged engagement -- typically when the pilot was maneuvering for a guns kill instead of a missile shot.

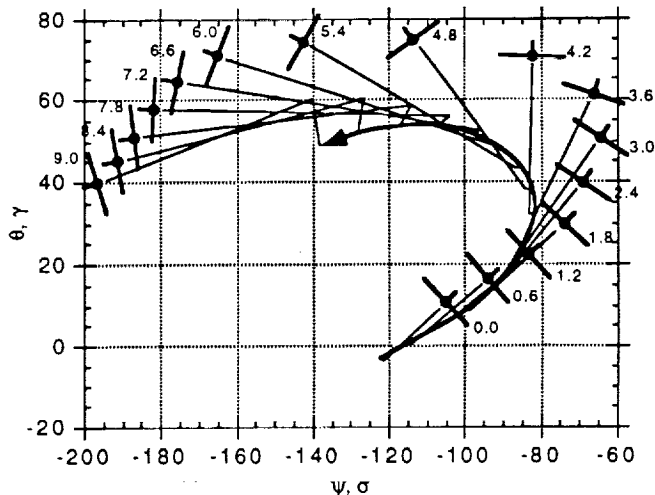
FOURTH NASA HIGH ALPHA CONFERENCE

E I D E T I C S

F-16 FVC 1v1 WVR - TYPICAL TRACKING MANEUVER



STANDARD F-16



STD NOSE + RNBS

INITIAL ENCOUNTER

While the differences observed during prolonged WVR air combat were not particularly surprising given the increased aerodynamic capability of the FVC enhanced aircraft, some interesting results developed from the initial engagement. The 1v1 scenario begins with both aircraft at the same altitude and speed on reciprocal headings. The aircraft were offset laterally approximately 0.9 miles from one another. The engagements began with both aircraft turning toward the other to obtain a missile or gun solution.

The initial engagements fell into three groups as sketched in the figure. The standard F-16 had roughly the same turn rate as the opposing aircraft and the first pass would be close to nose-to-nose. The two conventional control modifications had a moderate turn rate advantage and would acquire the target earlier. The FVC enhanced configurations had a tremendous turn rate and turn radius advantage and would be in a missile firing position long before the other aircraft.

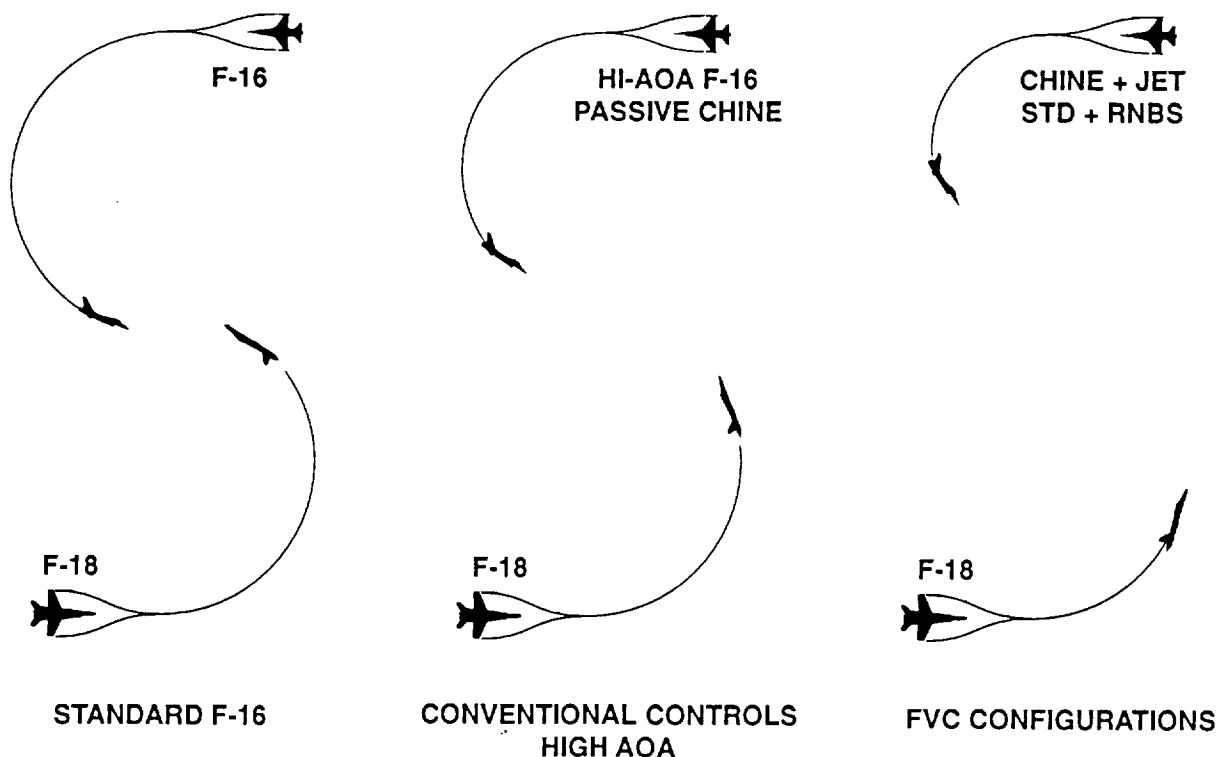
Examination of the angles of attack used during the turn explains the turn rate difference.

Configuration	Maximum AOA Used
Std F-16	26-28°
Passive Hi-AOA	30-35°
FVC Config's	40-45°

The trimmed lift coefficient of the five configurations over these angles of attack are very close to the same. The large difference in turn rate is due to the additional thrust component ($\approx 40\%$) at higher angles of attack.

The passive airframes have the same high angle of attack capability as the FVC airframes but the pilot was unwilling to use the capability, citing a bad feel and lack of confidence in the aircraft response. The passive chine configuration was stable at high angles of attack, but not controllable. The pilot soon learned to manually limit the angle of attack to a more moderate level where some degree of lateral-directional control remained. Even though the initial encounter was mostly a pure roll and pull maneuver, not requiring agile velocity vector rolls, the added control provided by FVC gave the pilot the confidence to fully utilize the pitch plane agility offered by the hi-AOA modifications.

F-16 FVC 1v1 WVR - INITIAL ENCOUNTER



CONCLUSIONS

FVC FROM STATIC AND ROTARY WIND TUNNEL TESTS:

Forebody vortex control is effective at angles of attack above 30°

Jet blowing is not greatly effected by a rotary flow field

Slot blowing is more effective on the leeward side during rotation.

Both the single rotating strake and the Rhino Horn increase the anti-spin tendency when undeflected.

The time lag due to onset and decay of blowing is on the order of the time it takes to deflect a conventional rudder.

FVC GAVE LARGE COMBAT ADVANTAGE:

ENVELOPE OPENED TO HI AOA

The configurations were stable, controllable and had predictable responses. The increased angle of attack envelope resulted in a large turn rate and turn radius advantage.

INCREASED CONTROL OF MANEUVER PLANE

Forebody vortex control gave velocity vector roll control allowing the maneuver plane to be changed without unloading from high angle of attack.

DIFFERENT FLYING TECHNIQUE, EASIER

This resulted in a smoother, more continuous approach to the target. Adjustments to the plane of the primary maneuver could be made during the approach to capture.

MORE MANEUVER OPTIONS

A larger variety of defensive and offensive maneuvers are available for the pilot to choose from allowing more shot opportunities.

CONCLUSIONS

F/A-18 -- FVC IN ROTARY FLOW FIELD

- FOREBODY VORTEX CONTROL IS EFFECTIVE AT ANGLE OF ATTACK ABOVE 30°.
- JET BLOWING IS NOT GREATLY EFFECTED BY A ROTARY FLOW FIELD.
- SLOT BLOWING IS MORE EFFECTIVE ON LEEWARD SIDE DURING ROTATION.
- SINGLE STRAKE AND RHINO INCREASE THE ANTI-SPIN TENDENCY.
- BLOWING TIME LAG IS ON THE ORDER OF CONVENTIONAL CONTROL DEFLECTION TIMES.

F-16 -- FVC IN COMBAT

FOREBODY VORTEX CONTROL GAVE A LARGE COMBAT ADVANTAGE DUE TO:

- FLIGHT ENVELOPE OPENED TO HIGH ANGLE OF ATTACK.
- INCREASED CONTROL OF MANEUVER PLANE.
- A DIFFERENT, EASIER FLYING TECHNIQUE.
- MORE MANEUVER OPTIONS AVAILABLE.